(19) Europäisches Patentamt
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(11) EP 0 715 092 A2

(12) EUROPEAN PATENT APPLICATION

(43) Date of publication:
05.06.1996 Bulletin 1996/23

(51) Int Cl.6: F16F 15/00, G10K 11/178

(21) Application number: 95308349.0

(22) Date of filing: 21.11.1995

(84) Designated Contracting States:
DE FR GB

(30) Priority: 02.12.1994 US 348527

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(54) **Vibration damping system using active negative capacitance shunt circuit with piezoelectric reaction mass actuator**

(57) Boring bar (19,20) vibration damping is improved by a novel use of the electromechanical properties of the piezoelectric actuator material (17). A negative capacitance shunt circuit (35) is provided in which a voltage-controlled voltage-source continuously simulates a negative capacitance that is substantially equal in magnitude but opposite in phase to the capacitance of the piezoelectric material (17). The negative capacitance is shunted across the piezoelectric device (17), effectively compensating for the capacitance of the device across a broad frequency band. The voltages generated in the piezoelectric element in response to mechanical deformation induced by broadband vibrations of the structure during damping operations, may then be completely resistively dissipated., thereby enhancing the mechanical damping.

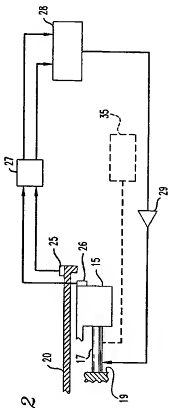


FIG. 2

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Printed by Jouve, 75001 PARIS (FR)

## Description

### FIELD OF THE INVENTION

This invention relates to mechanical vibration damping devices; and more specifically to improved use of piezoelectric actuators employed in such devices.

### BACKGROUND OF THE INVENTION

Piezoelectric material is advantageously employed as the actuator in certain active mechanical vibration control apparatus because of its ability to generate substantial countervailing forces with relatively little mass. Additionally, using a piezoelectric element as the actuator makes electronically controlled damping of the overall system feasible and relatively simple when compared to alternative active control methods. The typical electronic control arrangement includes sensors for detecting the frequency and amplitude of undesired mechanical vibrations occurring on a surface or in an element; and control circuitry responsive to the sensed information for driving the power amplifier of the piezoelectric device. Additionally, the prior art suggests use of a shunt network disposed across the piezoelectric device electrodes. The shunt circuit can in theory substantially cancel the capacitance of the piezoelectric device, with the result that the mechanical damping provided by the device may be increased.

If the mechanical damping required is limited to relatively narrow frequency bands, passive control circuits can generate the requisite narrowband capacitive cancellation using for example L-C resonance circuits. However, realizing a practical active controller circuit in conjunction with capacitance cancellation for broadband vibration damping is more difficult, due to the complexity of the time-spatial distributed nature of the total piezoelectric device-mechanical system. The damping performance of systems suggested to date has been sub-optimal where the vibrations are broadband.

A prime example of the unrealized potential for active damping circuits augmented by a negative capacitance shunt is the boring bar machine tool. When machining stiff or thick-walled workpieces, chatter tends to occur at the bar's first resonant frequency. Embedded piezoelectric reaction mass actuators have been proposed, but none have achieved the needed degree of broadband damping which would allow for precise, uniform cutting.

### SUMMARY OF THE INVENTION

The broadband capacitive properties of the piezoelectric material are removed or canceled in accordance with the present invention, by a novel use of the electromechanical properties of the material. A negative capacitance shunt circuit is provided in which a voltage-controlled voltage-source continuously simulates a negative capacitance of equivalent magnitude which is shunted across the piezoelectric device, effectively compensating for the capacitance of the device across a broad frequency band. The total impedance of the combined shunt circuit and piezoelectric device is then much larger than that of the piezoelectric device alone. As a result, the voltages generated in the piezoelectric element in response to mechanical deformation induced by broadband vibrations of the structure during damping operations, may be completely resistively dissipated.

Advantageously, the voltage-controlled voltage source has both high voltage and medium current capabilities. In one embodiment, the shunt circuit is a simple feedback bridge arranged to have slightly less positive feedback through a selected circuit node comprising a capacitive divider, than it has negative feedback through a designated resistive branch circuit. This arrangement continuously simulates a negative capacitance with a value that nearly cancels the piezoelectric capacitance regardless of the distribution of the resonant frequencies of the mechanical system.

### DESCRIPTION OF THE DRAWING

FIG. 1 is a schematic drawing of a boring bar with a piezoelectric driver for an internal actuator mass;
FIG. 2 is a schematic drawing of an actuator control circuit;
FIG. 3 is a mechanical/electrical diagram illustrating use of the negative capacitance shunt; and
FIG. 4 is a circuit diagram of a novel active negative capacitance shunt circuit.

### DETAILED DESCRIPTION OF AN ILLUSTRATIVE EMBODIMENT

In FIG. 1, a tool or other element subject to vibration, which in the illustration is a boring bar 10, is mounted in a fixed holder 11. The tool head 12 mounts a metal cutting tool bit 13. An interior chamber 14 formed within the exterior walls 20 at the tool head 12 contains an actuator mass 15. Mass 15 is mounted on a hinge 16 fixed to floor 19 of chamber 14. A piezoelectric stack 17 is positioned between one surface of mass 15 and floor 19, such that energizing of the stack will cause the mass to pivot about hinge 16. Advantageously, a pre-load spring 18 is also affixed between mass 15 and floor 19. Arrangements such as the preceding are known in the art, as exemplified for example, in U. S. Patent 5, 170, 103 issued Dec. 8, 1992.

In FIG. 2, a generalized prior art form of active control circuit for driving piezoelectric stack 17 is shown in solid line. It includes accelerometer 25 which senses acceleration of the boring bar 10 as it experiences mechanical chatter during a cutting operation; and actuator mass accelerometer 26 which senses acceleration of the mass 15 caused by the drive circuit as well as by external mechanical forces. Signals from sensors 25, 26

are converted in integrator 27 to respective indicia of displacement of the boring bar 10 in the vicinity of bit 13, and of the actuator mass 15. These signals are received by computer 28, which uses them to generate specific control signals for modulating a power amplifier 29 The output of amplifier 29 applies a control voltage to piezoelectric stack 17, which is varied to continuously reduce the displacement of the tool bit 13, and thus reduce the chatter.

In accordance with the invention, a negative capacitance shunt circuit 35 is shown in dashed lines connected to stack 17. Although it is shown as separate from the active control circuit in FIG. 2, it should be understood that shunt circuit 35 could be designed to be part of, or to augment, the active control circuit. Alternatively, it is envisioned that the shunt circuit 35 may be used in lieu of a conventional active control circuit in some circumstances. The details of an illustrative embodiment of shunt circuit 35 are explained hereinafter.

Because of the mechanical motion experienced by piezoelectric stack 17, a mechanical-to-electrical coupling exists, causing the device 17 to generate voltage and current waveforms. It has been realized that these waveforms can be advantageously exploited to produce a desirable mechanical damping effect. The chart of FIG. 3 shows the disturbing force F caused by the cutting of metal, which is transmitted to an overall mechanical system consisting in this illustration of the boring bar 10 and its components seen in FIG. 1. The mechanical-to-electrical coupling occurring in piezoelectric stack 17 generates a voltage across the piezoelectric electrodes as well as a current through the piezoelectric material. One strategy for taking advantage of the effects of this motion-induced voltage and current is to use a negative capacitance shunt.

Analysis further demonstrates that the impedance denoted $Z_{total}$ in FIG. 3 is the total electrical impedance of the piezoelectric stack 17 in parallel with the shunt circuit 35, and includes a capacitive component Cp. Shunt circuit 35 connected in parallel with stack 17 contains circuitry which ideally for all resonant frequencies has a driving-point impedance given by the following:

$$(1) \qquad E(jw)/I(jw) = -1/j\, C_p$$

where E is a voltage across $C_p$ and I is a current entering shunt circuit 35, as depicted in FIG. 3. Then, the shunt electrically looks like a capicatance of $-C_p$.

The objective which prior art control circuits has not achieved, is to generate a shunt impedance $Z_{shunt}$ which makes $Z_{total}$ effectively an open circuit at any frequency, whereby the shunt capacitance is continually made equal in magnitude to the stack capacitance, but opposite in phase.

FIG. 4 shows an advantageous configuration for an active negative capacitance shunt circuit 35 in accordance with the present invention. ~~The~~ circuit is a positive feedback arrangement using a voltage-controlled voltage source to generate the desired negative capacitance. Circuit 35 contains an operational power amplifier 40 which may be an Apex Microtech item PA-85 more fully described in Data Book Vol. 6 of the APEX Microtechnology Corp. of 5980 N. Shannon Drive, Tucson. Arizona. The numbered ports on the commercially available item are as shown in FIG. 4. Power amplifier 40 has the requisite high voltage and medium current capabilities found to be necessary for compatibility with the electrical properties of the particular piezoelectric stack material. The PZT piezoelectric material used in the present illustration has a peak-to-peak voltage limit of 120 volts, a capacitance $C_p$ of 20 microfarads and a frequency range of DC to 250 Hz. In this case, the maximum drive current is about 1 ampere. Specific requirements of active circuits using the invention will depend on the type of piezoelectric material used and bandwidth of control.

Amplifier 40 is connected across device 17 via an input/output circuit comprising terminal 41. A tuning resistor 42 advantageously is placed across the input/output terminal leads, to provide the optimum mechanically-damped response. The exact range of values for this resistance may be determined through computer simulation using a suitable model of the system dynamics. Alternatively, the resistance value may be selected empirically through measurements of mechanical vibration levels resulting from an induced forcing function applied to the actual mechanical system.

A load capacitor 43 connected from the positive terminal port 4 to port 1 is selected in accordance with one aspect of the invention such that:

$$(2) \qquad C_{load}/C_p \leqq R_s/R_f$$

The $R_f$, $R_s$ voltage divider sets the negative feedback non-inverting operational amplifier gain. Then, the ratio $R_f/R_s$ is the same as the ratio $C_p/C_{load}$ for identical positive and negative feedbacks.

The feedback arrangement of FIG. 4 advantageously is set to generate slightly less positive feedback through the $C_{load}$-$C_{p\ voltage}$ divider than negative feedback through the $R_f$-$R_s$ voltage divider. This is the reason for the inequality condition in Equation (2).

If positive feedback exceeds negative feedback, it implies that the whole circuit has negative equivalent components, and it will be unstable. The voltage-controlled voltage-source negative capacitance configuration described therefore is stabilized additionally by providing compensation of the frequency response of operational amplifier 40. This may be achieved, for example, by components $R_1$, $R_2$ and $C_c$ shown in FIG. 4. The component values are selected for best amplifier stabilization as described in the above-noted APEX publication for the P85 device used herein.

In other words, in addition to the inequality in Equation (2), which is a total systems stability requirement, the operational amplifier 40 should have sufficient gain and phase margin in circuit 35 to prevent oscillations in the overall system, consisting as already noted in con-

nection with FIG. 3 of interacting mechanical, piezoelectric and negative capacitance elements. The compensation required for the amplifier is determined by the gain-phase margin that is practically achievable, the type of amplifier used, and the nature of the piezoelectric and mechanical system involved.

Analysis of the described negative capacitance circuit of the present illustration when used in a boring bar application, indicates that as much as 20 dB reduction in mechanical resonant response can be obtained compared to a boring bar without vibration damping. Further, at least a 6dB improvement over typical passive shunt circuits is obtained.

In summary, a wideband damping performance in a piezoelectric vibration damper is achieved in accordance with the invention by effectively and reliably removing the capacitive property of the piezoelectric material in the actuator stack, leaving the material's high resistance as the dissipative element for the voltage generated in the device. The electrical energy thus dissipated increases the mechanical damping ratio by from 0.01% to 0.3 %, where 1.0% is defined as the critical damping value for a resonant system.

## Claims

1. A vibration-reducing device for damping broadband vibrations of a structure, comprising:

   an actuator connected to said structure and comprising piezoelectric material, said material having a broadband capacitive reactance;
   a negative capacitance circuit connected in shunt relation to said material, said circuit comprising means for continuously simulating a negative capacitance of equivalent magnitude but opposite in phase to said capacitive reactance of said piezoelectric material;
   the total impedance of the combined shunt circuit and said piezoelectric device being substantially larger than that of said piezoelectric material alone; and
   means for resistively dissipating the voltages generated in said piezoelectric material in response to mechanical deformation thereof induced by broadband vibrations of said structure during damping operations of said actuator.

2. Apparatus in accordance with Claim 1, wherein the total electrical impedance of said piezoelectric material in parallel with said shunt circuit and the driving-point impedance of said shunt circuit are related such that said shunt circuit continuously simulates a predetermined negative capacitance which makes said total electrical impedance effectively an open circuit at any operating frequency.

3. Apparatus in accordance with Claim 2, wherein said simulating means comprises a voltage-controlled voltage-source.

4. A vibration-reducing device for damping broadband vibrations in a structure, comprising:

   an actuator connected to said structure and comprising a piezoelectric stack having a broadband capacitive reactance $C_p$;

   negative capacitance circuit means connected in shunt relation to said stack for continuously simulating a capacitive reactance of a magnitude substantially equivalent to $C_p$ but opposite in phase, said means comprising:

      an operational amplifier having positive and negative feedback loops;

      an input/output circuit connecting said amplifier in shunt relation across said stack;

      a tuning resistor disposed across said input/output circuit for tuning said negative capacitance circuit means to a predetermined optimum mechanically-damped response for the particular said structure;

      a resistive voltage divider comprising first and second series-connected resistors, said second resistor being connected across said amplifier, said resistive

   divider determining the negative feedback non-inverting gain of said amplifier; and

      a load capacitor connected across said amplifier and forming a capacitive voltage divider with said stack capacitance,

      the ratio of the impedance of said load capacitor to that of said stack capacitance being equal to or slightly greater than the ratio of the resistive values of said first and said second resistors;

      whereby said two-named ratios are substantially the same for identical positive and negative feedback performance of said amplifier.

5. Apparatus in accordance with Claim 4, wherein said

   feedback loops generate slightly less positive feedback through
   said capacitive voltage divider than negative

feedback through said resistive voltage divider.

6. Apparatus in accordance with Claim 5, further comprising circuit means connected to said amplifier for compensating for frequency response of said amplifier, thereby to stabilize said negative capacitance circuit means.

7. Apparatus in accordance with Claim 6, wherein the piezoelectric material of said stack is PZT; and wherein said operational amplifier is a high voltage, medium current operational amplifier.

8. Apparatus in accordance with claims 1, 2, 3, 4, 5, 6, or 7,

   wherein said structure is a boring bar machine tool having a chambered cutting end; and wherein said actuator is mounted in said chamber.

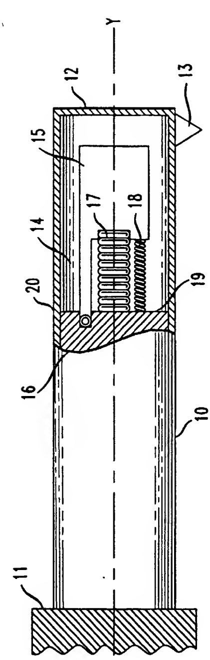



FIG. 1

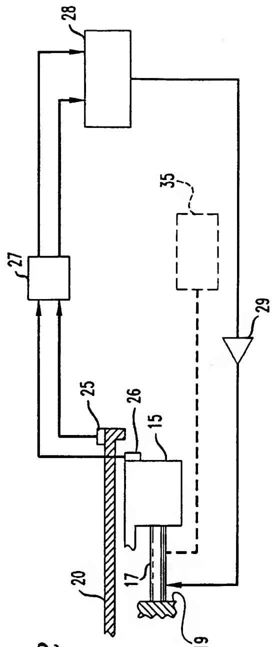



FIG. 2

*FIG.3*

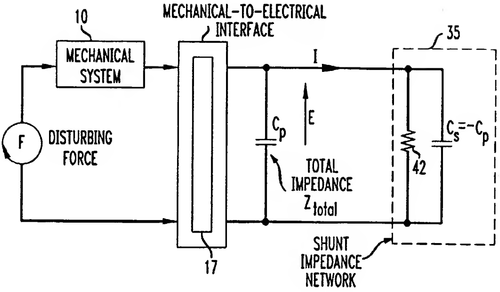
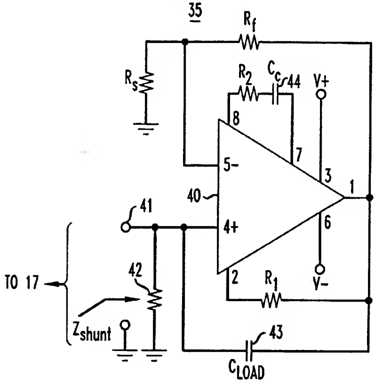

10
MECHANICAL SYSTEM
MECHANICAL-TO-ELECTRICAL INTERFACE
35
I
E
$C_p$
$C_s = -C_p$
F
DISTURBING FORCE
42
TOTAL IMPEDANCE $Z_{total}$
17
SHUNT IMPEDANCE NETWORK

*FIG.4*


35
$R_f$
$R_s$
$R_2$
$C_c$
44
V+
8
7
5-
3
1
40
41
4+
6
TO 17
42
2
$R_1$
V-
$Z_{shunt}$
43
$C_{LOAD}$

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| (51) International Patent Classification 7 : B23B 29/12, F16F 15/00 | A1 | (11) International Publication Number: WO 00/25963 (43) International Publication Date: 11 May 2000 (11.05.00) |
|---|---|---|

(21) International Application Number: PCT/SE99/01884

(22) International Filing Date: 19 October 1999 (19.10.99)

(30) Priority Data:
9803606–4 22 October 1998 (22.10.98) SE

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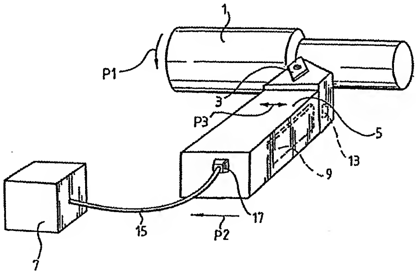
(81) Designated States: AE, AL, AM, AT, AT (Utility model), AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CR, CU, CZ, CZ (Utility model), DE, DE (Utility model), DK, DK (Utility model), DM, EE, EE (Utility model), ES, FI, FI (Utility model), GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SK (Utility model), SL, TJ, TM, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZW, ARIPO patent (GH, GM, KE, LS, MW, SD, SL, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).

**Published**
*With international search report.*
*In English translation (filed in Swedish).*

(54) Title: METHOD AND DEVICE FOR CONTROLLING A TURNING OPERATION




(57) Abstract

The invention relates to a device for increasing the surface smoothness of a turned surface, said device comprising a control system with a control unit (7) and an actuator (9) connectible to the control unit and connectible with a tool holder (5). The actuator is adapted to impart a vibrating motion in the lateral direction to the tool holder. The invention also relates to a method for increasing the surface smoothness of a turned surface, comprising the step of controlling the vibrations of the tool holder during turning. The method also comprises the step of imparting a vibrating motion in the lateral direction to the tool holder. Moreover, the invention relates to a turning lathe and a turning tool holder which like the device are designed to generate said vibrating motion in the lateral direction.

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# METHOD AND DEVICE FOR CONTROLLING A TURNING OPERATION

## Field of the Invention

The present invention relates to a method and a device for controlling a turning operation, more specifically a method, a device, a turning tool holder and a turning lathe for increasing the surface smoothness of a turned surface.

## Background Art

When a workpiece is worked by means of a lathe, a certain degree of unevenness always arises in the turned surface. The unevenness can be resembled to stripes or threads and arises owing to the cutting edge of the working tool having a limited nose radius. The tools are manufactured with a plurality of different standard radii. The radius of the cutting edge results, in combination with the feeding, in a surface which is not quite smooth. A low feeding speed certainly gives a smoother surface but is irrational in industrial manufacture and therefore does not solve the problem.

For reasons of rationality and expense, much would be gained if, in spite of a relatively high feeding speed, it would be possible to obtain a surface having such a high smoothness that the finishing which today is often necessary can be eliminated or, in any case, be significantly reduced.

## Summary of the Invention

An object of the present invention is to provide a method and a device for increasing the surface smoothness in turning.

The object is achieved by a device and a method according to claims 1 and 12, respectively.

## Brief Description of the Drawings

The invention and further advantages thereof will now be described in more detail by way of embodiments with reference to the accompanying drawings, in which

Fig. 1 is a schematic perspective view of an embodiment of the inventive device;

Fig. 2 is a schematic view of an embodiment of a tool holder according to the invention; and

Fig. 3 is a schematic plan view of the device in Fig. 1.

Description of an Embodiment

Fig. 1 illustrates essentially an embodiment of the device and also of the tool holder according to the invention. Reference numeral 1 indicates a workpiece which is arranged in a lathe and rotates in the direction indicated by arrow P1. The workpiece 1 is worked by means of a tool 3, here referred to as insert, which is rigidly connected to a tool holder 5, here referred to as insert holder. The device comprises a control system with a control unit 7 and two actuators 9, 11, one of which is indicated by dashed lines in Fig. 1 and both of which are shown in Fig. 2, which illustrates the actual tool holder 5 in a different view.

Each actuator 9, 11 comprises an active element 9, 11, which here is a piezoceramic element. A piezoceramic element can in turn be designed as a unit or advantageously be made up as a so-called stack and/or of several partial elements. Thus the element can be a solid body or a plurality of individual, but composed and interacting bodies. The active elements 9, 11 are embedded in the body of the tool holder 5, which is also referred to as shaft. More specifically, they are fixed by casting. The casting is carried out by forming for each active element 9, 11 a recess in the body of the tool holder, whereupon the active element 9, 11 is placed therein and covered by casting. The active element 25, 27 is glued preferably to the bottom surface of the recess. The active elements 9, 11 are embedded fairly close to the surface of the tool holder 5, i.e. close to its lateral surfaces 5d, 5e. Moreover, the active elements 9, 11 are plate-shaped and are oppositely arranged in parallel.

The active elements 9, 11 are arranged on each side of the centre axis of the tool holder 5, said centre axis being designated I-I in Fig. 2. An active element 9, 11 is characterised in that it changes dimension when an electric voltage is applied across the same. The dimensional change is related to the voltage. Moreover, the tool 3 is mounted on the upper side 5c of the holder 5.

The control unit 7 is via a conduit 15 and a terminal 17 connected to the tool holder 5. Inside, i.e. embedded in, the tool holder 5 extend to/from the terminal 17 conductors 30-33 of the active elements, or the piezoceramic elements 9, 11, see Fig. 3. The piezoceramic elements 9, 11 are elongate in the longitudinal direction of the tool holder 5, and the conductors 30-33, which are connected in pairs to a piezoceramic element 9, 11 each, are connected to the front ends 11a, 9a and rear ends 11b, 9b thereof.

The device operates as follows. The tool 3 and the tool holder 5 are fed in the direction of arrow P2 at a certain feeding speed M. The workpiece rotates in the direction of arrow P1 at a certain cutting speed. The combination of M>O, and the edge of the tool 3 having a radius causes remaining, helically extending ridges on the worked surface. More than anything, the ridges resemble stripes. The control unit 7 feeds control voltages to the actuators, more specifically to the piezoceramic elements 9, 11. When voltage is applied to the piezoceramic elements 9, 11, they are thus extended to a greater or smaller degree depending on the amplitudes of the voltages. In other words, each piezoceramic element 9, 11 obtains a dimensional change in its longitudinal direction, which also is the longitudinal direction of the tool holder 5. The piezoceramic elements 9, 11 are preferably embedded in the tool holder 5 so that their boundary surfaces abut directly against the material of the body of the tool holder 5. The piezoceramic elements 9, 11 have opposite power-transmitting surfaces in the

form of their end faces at the ends 9a, 9b, 11a and 11b. The end faces transfer the longitudinal changes of the piezoceramic elements 9, 11 in the body of the tool holder 5. Since the piezoceramic elements 9, 11 are spaced from the centre axis I-I of the tool holder 5, the longitudinal changes generate turning moments which in the illustrated arrangement of the piezoceramic elements 9, 11 show themselves as bending. By the expression "spaced from the centre axis" is meant that the centre axes of the piezoceramic elements 9, 11 do not coincide with the centre axis of the tool holder 5. If the centre axes should coincide, no bending moment would be obtained, but merely a pure longitudinal change of the tool holder 5. The same would apply if the two piezoceramic elements 9, 11 should be longitudinally changed concurrently and to the same extent. The forces induced by means of the piezoceramic elements 9, 11 bend the front end 5a of the tool holder 5 in the lateral direction, from side to side, thanks to the control voltages to the respective piezoceramic elements 9, 11 being applied so that the piezoceramic elements 9, 11 are longitudinally changed in opposition to each other. Thus the tool holder 5 is made to move in a vibrating manner alternatingly in and against the direction of feed.

The turning moments thus act about an axis which is perpendicular to the centre axis I-I and produce a vibrating motion in the lateral direction, as indicated by arrow P3. By the lateral vibrations, the groove which the tool forms in the surface of the workpiece 1 is widened and the stripes are worked off. The appearance of the control voltages, however, is important to the result. In a preferred embodiment of the device, the control unit 7 generates composite control voltages having a wide, noise-like frequency content. A factor in this context, however, is the feeding speed M which may vary quite considerably between different turning operations. The feeding speed is above all important to the amplitude

of the control voltages. A preferred embodiment of the inventive device therefore comprises a control unit which is adjustable in respect of the amplitude of the control voltages. As a result, different amplitudes can be generated.

Alternative Embodiments

The above specification essentially constitutes a non-limiting example of how the device according to the invention can be designed. Many modifications are possible within the scope of the invention as defined in the appended claims. Below follow some examples of such modifications.

In an alternative embodiment, the control unit also comprises a means for adjusting the frequency content of the control voltages.

In a further alternative embodiment, the control unit has preset values of frequency and amplitude of the control voltages.

In one more alternative embodiment of the inventive device, the control unit 7 operates with fed-back control, which means that it strives to set the amplitude of the vibrations at a suitable level by means of feedback from sensors. The control unit 7 can be selected among many different types, such as analog fed-back control unit, conventional PID regulator, adaptive regulator or some other suitable type of control unit. To achieve said fed-back control, the sensors 13, 15 are arranged in the tool holder 5 as illustrated in the Figures. The sensors 13, 15 are arranged in front of the actuators 9, 11. By "in front of" is meant closer to the end of the tool holder 5 where the tool 3 is mounted, said end being naturally considered the front end 5a of the tool holder 5. The opposite end 5b thus is the rear end of the tool holder 5. The sensors 13, 15 consist of piezoelectric crystals which generate an electric voltage when subjected to forces. The sensors 13, 15 are preferably, like the actuators 9, 11, embedded in the body of the tool holder

5 and are electrically connected with the control unit 7 via conductors which are connected in the same way as the conductors 30-33 of the actuators, but which for reasons of clarity are not shown.

The sensors 13, 15 are subjected to alternating pulling and pressing forces. Each sensor 13, 15 then generates a sensor voltage which varies concurrently with the variations in force. The sensor voltages are detected and analysed by the control unit 7, which controls the actuators 9, 11 in accordance with the desired amplitude of the sensor voltages. The regulation which this involves is carried out by means of a control algorithm. A large number of known control algorithms are available.

In one more alternative embodiment of the device according to the invention, the control unit takes the present feeding speed into consideration, i.e. the control unit has a means for indicating which feeding speed is appropriate for the turning operation which is to begin. In an NC-controlled lathe, the means can even automatically collect this information directly from the NC control system.

A further possible modification is to change the number of actuators. In the simplest case, one actuator is arranged in the tool holder. To achieve a more symmetric application of forces on the tool holder, it is however advantageous to arrange at least the above-described pair of actuators in the described opposite arrangement. There is nothing to prevent that a larger number of actuators are arranged which are oppositely arranged in pairs in the tool holder. For practical reasons and in view of the production costs, it is however disadvantageous to embed a large number of actuators.

The method of mounting the active elements may be varied. In addition to the above-mentioned way of mounting, they can be, for example, premounted in a mould in which the tool holder is cast. If they are fixed by cast-

ing later, as has been described above, they can either be covered with the same material as that of which the tool holder is made or with some other convenient material. Moreover it is possible to use alternatives to the above-described, preferred mounting, where the elements are certainly glued to the base of the recess but two opposite power-transmitting surfaces essentially generate the turning moments. Such an alternative means that the dimensional change is completely transferred via the glue joint, which in principle is possible with today's strongest adhesives. In that case, the abutment of the above-mentioned power-transmitting surfaces can be omitted, which reduces the claims for adaptation. Also other variants are contained within the scope of the invention.

The active elements are in respect of form not bound to be rectangularly parallelepipedal and plate-shaped as the shown elements, but the form may vary. The plate shape, however, is advantageous since it contributes to minimising the volume of the element. Moreover, an elongate form is an excellent property which also contributes to imparting to the element a small volume. It is preferred that the dimensional changes occur in the longitudinal direction of the element.

Basically, other types of actuators and ways of mounting than those described above are contained within the scope of the invention. However, embedded, active elements have obvious advantages.

CLAIMS

1. A device for increasing the surface smoothness of a turned surface, said device comprising a control system comprising a control unit (7) and an actuator (9, 11) connectible to the control unit and connectible with a tool holder (5), characterised in that said actuator is adapted to impart a vibrating motion in the lateral direction to the tool holder.

2. A device as claimed in claim 1, characterised in that said actuator (9, 11) comprises an active element (9, 11) which is embeddable in the body of the tool holder (5).

3. A device as claimed in claim 1 or 2, characterised in that the control system comprises a vibration sensor (13, 15) connectible to the control unit (7) and connectible with the tool holder (5), that said vibration sensor is adapted to detect vibrations of the tool holder in the lateral direction, and that the control unit is adapted to control the vibrating motion by controlling the actuator according to sensor signals from the vibration sensor.

4. A turning tool holder, characterised in that it comprises an actuator (9, 11) which is adapted to impart a vibrating motion in the lateral direction to the turning tool holder (5).

5. A turning tool holder as claimed in claim 4, characterised in that said actuator (9, 11) comprises an active element (9, 11) which is embedded in the body of the turning tool holder (5).

6. A turning tool holder as claimed in claim 4 or 5, characterised in that it comprises at least one pair of active elements, the active elements included in the pair being oppositely arranged on each side of the centre axis of the turning tool holder (5).

7. A turning tool holder as claimed in claim 4, 5 or 6, c h a r a c t e r i s e d in that it comprises a vibration sensor (13, 15) which is embedded in the body of the turning tool holder (5).

8. A turning lathe comprising a tool holder (5) and an actuator (9, 11) connected with the tool holder, c h a r a c t e r i s e d in that the actuator is adapted to impart a vibrating motion in the lateral direction to the tool holder.

9. A turning lathe as claimed in claim 8, c h a r - a c t e r i s e d in that it comprises a control system, the control system comprising a control unit (7) and a vibration sensor (13, 15) connected to the control unit and connected with the tool holder, that said actuator is connected to the control unit, that said vibration sensor is adapted to detect the vibrations of the tool in the lateral direction, and that the control unit is adapted to control the vibrating motion by controlling the actuator according to sensor signals from the vibration sensor.

10. A turning lathe as claimed in claim 8 or 9, c h a r a c t e r i s e d in that said actuator (9, 11) comprises an active element (9, 11) which is embedded in the body of the tool holder (5).

11. A turning lathe as claimed in claim 10, c h a r a c t e r i s e d in that said active element (9, 11) is a piezoceramic element (9, 11).

12. A method for increasing the surface smoothness of a turned surface, comprising the step of controlling the vibrations of a tool holder during turning, c h a r a c t e r i s e d by the step of imparting a vibrating motion in the lateral direction to the tool holder.

13. A method as claimed in claim 12, c h a r a c - t e r i s e d by the step of imparting to the tool holder said vibrating motion by means of an actuator comprising

an active element embedded in the body of the tool holder.

14. A method as claimed in claim 13, c h a r a c t e r i s e d by the step of controlling in a fed-back manner said vibrating motion by detecting the lateral vibration of the tool holder and controlling said actuator according to said lateral vibration.

15. A method as claimed in any one of claims 12-14, c h a r a c t e r i s e d by the step of adjusting said vibrating motion to the feeding speed.

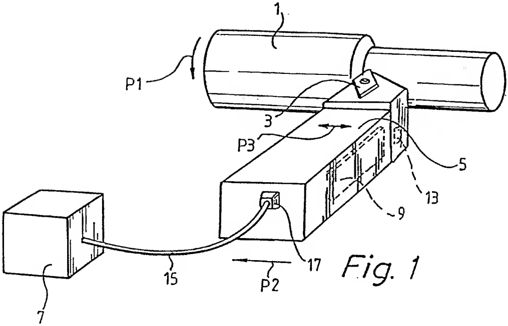


Fig. 1

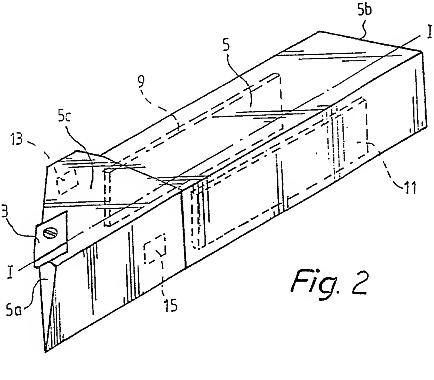


Fig. 2

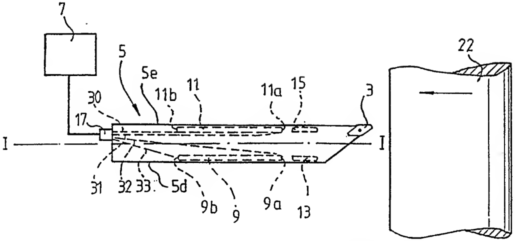


Fig. 3

# INTERNATIONAL SEARCH REPORT

International application No.
PCT/SE 99/01884

## A. CLASSIFICATION OF SUBJECT MATTER

IPC7: B23B 29/12, F16F 15/00

According to International Patent Classification (IPC) or to both national classification and IPC

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Minimum documentation searched (classification system followed by classification symbols)

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## C. DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| X | US 5170103 A (ROUCH ET AL), 8 December 1992 (08.12.92), column 4, line 26 - line 34; column 6, line 22 - line 45, figures 2,7, abstract | 1-5,7-15 |
| Y | | 6 |
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| Y | US 4849668 A (CRAWLEY ET AL), 18 July 1989 (18.07.89), column 5, line 20 - line 25, figure 4, abstract | 6 |
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| X | Patent Abstracts of Japan, Vol 12,No 448, M-768 abstract of JP 63-180401 A (MITSU ENG & SHIPBUILD CO LTD), 25 July 1988 (25.07.88) | 1-5,7-15 |
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[X] Further documents are listed in the continuation of Box C. [X] See patent family annex.

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| Y | | 6 |
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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 7 :
B23B 29/12, F16F 15/00

A1

(11) International Publication Number: WO 00/25964

(43) International Publication Date: 11 May 2000 (11.05.00)

(21) International Application Number: PCT/SE99/01885

(22) International Filing Date: 19 October 1999 (19.10.99)

(30) Priority Data:
9803607-2 22 October 1998 (22.10.98) SE

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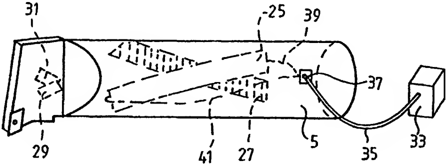
(81) Designated States: AE, AL, AM, AT, AT (Utility model), AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CR, CU, CZ, CZ (Utility model), DE, DE (Utility model), DK, DK (Utility model), DM, EE, EE (Utility model), ES, FI, FI (Utility model), GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SK (Utility model), SL, TJ, TM, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZW, ARIPO patent (GH, GM, KE, LS, MW, SD, SL, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).

**Published**
*With international search report.*
*In English translation (filed in Swedish).*

(54) Title: METHOD AND DEVICE FOR VIBRATION CONTROL III




(57) Abstract

The invention relates to a device for vibration control in a machine for boring, the machine comprising a cutting tool (3) supported by a tool holder (5). The device comprises a control unit (33), a vibration sensor (29, 31) connectible to the control unit, and an actuator (25, 27) connectible to the control unit. The actuator comprises an active element (25, 27) which converts an A.C. voltage supplied by the control unit to the actuator into dimensional changes. The active element is adapted to be embedded in the body of the tool holder and is adapted to be embedded in such a manner that said dimensional changes impart turning moments to the body of the tool holder. The invention further relates to a method for vibration control in boring. The invention also relates to a tool holder (5) for boring.

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# METHOD AND DEVICE FOR VIBRATION CONTROL III

## Field of the Invention

The present invention relates to a method and a device for vibration control, and more specifically a method and a device for vibration control in boring, and a tool holder for vibration control in boring.

## Background Art

In boring, dynamic motion arises between the tool and the workpiece. The motion is largely due to the fact that the chip-forming process, i.e. the removal of the generally relatively hard material from the workpiece, results in dynamic excitation of the tool, especially the tool holder. The dynamic excitation results in a dynamic motion, in the form of, for instance, elastic bending or torsion, of the tool and the tool holder. The chip-forming process is largely stochastic and the excitation appears in the form of tool vibrations and noise. In addition to thus causing problems in the working environment, the dynamic motion also affects the evenness of the surface of the workpiece and the service life of the tool.

It is therefore important to reduce the dynamic motion as far as possible. It has been known for long that the vibration problem is closely connected with the dynamic stiffness in the construction of the machine and the material of the workpiece. It has therefore been possible to reduce the problem to some extent by designing the construction of the machine in a manner that increases the dynamic stiffness. Moreover, it has recently been possible to increase the dynamic stiffness of the tool itself and the tool holder by active methods for controlling the response of the tool. This means that active control of the tool vibrations is applied.

The active control comprises the introduction of secondary vibrations, or countervibrations, in the tool by means of a secondary source which is called actuator. The actuator is operated in such manner that the control vibrations interfere destructively with the tool vibrations.

In boring, i.e. inside turning, the tool is affected by excitation forces in the cutting speed direction, i.e. the direction of rotation of the workpiece at the cutting edge of the tool, in the direction of feed, i.e. axially seen from the perspective of the workpiece, and in the radial direction, i.e. radially seen from the perspective of the workpiece. The radial direction thus is perpendicular to the cutting speed direction. There are no known solutions for reducing tool vibrations in boring. However, attempts have been made to solve the corresponding problem in outside turning. The excitation forces in outside turning correspond approximately to the excitation forces in boring, but there are essential differences in the response of the tool holders since their design differs.

US-4,409,659 discloses an example of active control of the tool vibrations in outside turning. An ultrasonic actuator is arranged on the tool and produces countervibrations in the tool. The operating current of the actuator is controlled according to physical parameters that are measured and by means of the work of the actuator are kept within defined limits. This construction is unwieldy since the actuator is a comparatively large component which must be mounted on a suitable surface of the tool. Moreover, the directive efficiency of an ultrasonic actuator is not quite distinct.

JP-63,180,401 discloses a very different solution in outside turning, where the actuator is built into the tool holder which holds a turning insert. A laterally extending through hole which is rectangular in cross-section is formed in the tool holder. A piezoelectric

actuator, in series with a load detector, is fixed between the walls that define the hole in the longitudinal direction of the tool holder. The load detector detects the vibrations and is used by a control unit to generate, via the actuator, countervibrations which reduce the dynamic motion. This construction necessitates a considerable modification of the tool holder and indicates at the same time that the designer has not been aware of the essence of the excitation process. In fact, the modification counteracts the purpose of the construction by reducing the stiffness of the tool holder in the most important directions, above all vertically, which in itself causes a greater vibration problem, or alternatively means that the dimensions of the tool holder must be increased significantly in order to maintain the stiffness. During outside turning, the rotating tool produces a downwardly directed force on the cutting edge. When the cutting edge offers resistance, material is broken away from the workpiece. In this context, most of the vibrations arise. In JP-63,180,401, one imagines that the surface of the workpiece is uneven (wave-like) and thus mainly excites the tool holder in its longitudinal direction. Via the actuator, one generates an oscillation in opposition towards the wave pattern and thus obtains a constant cutting depth.

There is thus a need for a solution which controls the most essential vibrations, which is intended for boring (or drilling turning) and which causes a minimum of negative effects, such as bulky projections of dynamically weakening modifications, and still has a good effect.

Summary of the Invention

An object of the present invention is to provide a well-functioning method and a well-functioning device for vibration control in boring.

The object is achieved by a device and a method according to the invention as defined in claims 1 and 7, respectively.

Another object of the present invention is to provide a tool holder arranged for vibration control.

The object is achieved by a tool holder according to claim 10.

The idea of embedding according to the invention at least one active element in the tool holder implies a minimal modification of the tool holder and at the same time uses the rapidity and the capability of changing dimensions of the active element in an optimal manner. The embedding is also advantageous by the device being usable in practice since it is protected against cutting fluids and chips. In addition to the prior-art devices not being designed for boring, they are designed in a manner which possibly makes them usable for laboratories, but not in the industry.

The device according to the invention is further adapted to impart a turning moment to the tool holder through the arrangement of the active element/elements. The corresponding actuator element in JP-63,180,401 is deliberately arranged so that the dimensional change occurs along the longitudinal axis of the tool holder, which does not result in a turning moment. This depends on an incomplete idea of what primarily causes the vibration problems. Thus one has not realised that the most important excitation forces have any other direction but parallel with the longitudinal axis of the tool holder. Even with this knowledge, the construction according to JP-63,180,401, however, is not easily adjustable to any other kind of mounting than the one shown.

## Brief Description of the Drawings

The invention and additional advantages thereof will now be described in more detail by way of embodiments with reference to the accompanying drawings, in which

Fig. 1 is a schematic perspective view of an arrangement of a workpiece and a tool holder with a mounted tool;

Fig. 2 is a schematic perspective view of an embodiment of the tool holder with a mounted tool according to the invention;

Fig. 3 is a schematic perspective view of another embodiment of the tool holder with a mounted tool according to the invention; and

Fig. 4 is a block diagram of an embodiment of a fedback control according to the invention.

Description of an Embodiment

In boring, a workpiece 1 is arranged in the turning lathe and is made to rotate at a certain cutting speed. Here the direction of rotation is indicated by arrow A. A turning tool 3, referred to as insert, is essentially rigidly mounted on a tool holder 5, which is referred to as boring bar. To remove material from the workpiece 1, the boring bar 5 is moved in a direction of feed indicated by arrow B. 7 designates the head of the boring bar 5, the head tapering towards the front end.

A preferred embodiment of the device according to the invention is shown in Fig. 3. It comprises a control unit 33, two actuators 25, 27 and two sensors or sensor elements 29, 31. The actuator 25, 27 comprise active elements, which here consist of piezoceramic elements. A piezoceramic element can in turn be designed as a unit or advantageously by made up as a so-called stack and/or of several partial elements. Thus, the element can be a solid body or a plurality of individual, but composed and interacting bodies. The active elements 25, 27 are characterised in that they change dimension when an electric voltage is applied across them. The dimensional change is related to the voltage. The active elements 25, 27 are embedded in, more specifically cast into, the body of the tool holder 5. The casting is carried out by forming for each active element 25, 27 a recess in the body of the

tool holder 5, whereupon the active element 25, 27 is arranged therein and covered by casting. The active element 25, 27 is glued preferably to the bottom surface of the recess. The piezoceramic elements 25, 27 are embedded fairly close to the surface of the tool holder 5, i.e. close to the circumferential surface thereof.

The sensors 29, 31 consist of piezoelectric crystals which generate an electric voltage when subjected to forces. Also the sensors 29, 31 are preferably covered by casting in the same way as the active elements 25, 27. The control unit 33 is, via a conduit 35 containing a plurality of conductors, and a terminal 37 mounted on the boring bar 5, connected to the sensors 29, 31 and the actuators 25, 27. For the sake of clarity, only those conductors 39, 41 are shown in the boring bar 5 which are connected to the one actuator 25, but of course conductors are also arranged for the other actuator 27 and for the sensors 29, 31. The conductors 39, 41 are also cast into the tool holder 5.

The mainly dynamic forces acting on the boring bar have the character of torsion. The piezoceramic elements 25, 27 are plate-shaped and elongate. By arranging them in an inclined position as shown in Fig. 3, i.e. with their longitudinal direction helically extended round the centre axis of the boring bar 5, they are essentially parallel with the resultants of the torsional forces in the body of the boring bar 5. The sensors 29, 31 are arranged correspondingly in the head 7 of the boring bar.

In an alternative embodiment as shown in Fig. 2, use is made of four active elements 9, 11, 13, 15 and four sensors 17, 19, 21, 23, which are oppositely arranged in pairs and in parallel, in the form of two pairs of sensors 17, 19 and 21, 23, respectively, and two pairs of active elements 9, 11 and 13, 15, respectively. The active elements 9, 11 of the first pair are arranged in opposing side portions of the boring bar 5. The active elements 13, 15 of the second pair are arranged in an

upper and a lower portion, respectively, of the boring bar 5. The sensors 17, 19, 21, 23 are arranged correspondingly in front of the active elements 9, 11, 13, 15 in the head 7 of the boring bar 5.

The vibration control is carried out as follows. Owing to the rotation of the workpiece 1, the chip-breaking process causes a force which, seen from the perspective of the workpiece, is tangentially directed and which acts on the insert 3. Owing to the fact that the cutting edge is spaced from the centre axis of the boring bar 5, a turning moment is generated, which shows itself as a torsional force in the boring bar 5. At the same time, the insert 3 and the boring bar 5 are exposed to forces which, seen from the perspective of the workpiece, are directed radially and axially, respectively, the axial force arising owing to the feeding in the direction of arrow B. The radially and axially directed forces cause turning moments in the form of bending. Because of the character of the chip-breaking process, said forces vary, and therefore the motions of the boring bar 5, which result from said forces, are perceived as mechanical vibrations. The vibrations occur in all directions, but the torsional vibrations are dominant.

In the embodiment in Fig. 3, the following applies. The vibrations of the boring bar 5, especially the head 7, are detected by means of the sensors 29, 31, which are subjected to alternating pulling and pressing forces. The piezoelectric sensors generate sensor signals in the form of A.C. voltages in response to the pulling and pressing forces. The control unit 23 detects the sensor signals and, in relation thereto, generates control signals in the form of control voltages, which the control unit supplies to the actuators 25, 27, more specifically to the ends of the piezoceramic elements 25, 27. The piezoceramic elements 25, 27 widen more or less in the longitudinal direction according to the frequencies and amplitudes of the control signals. The longitudinal

changes of the piezoceramic elements 25, 27 impart, through the arrangement of the piezoceramic elements 25, 27, turning moments to the boring bar 5 which generate torsional forces in the body of the boring bar 5. The power transmission to the material of the body of the boring bar 5 occurs wholly or essentially via the power-transmitting surfaces of the piezoceramic elements 25, 27. The power-transmitting surfaces consist of the end faces of the piezoceramic elements 25, 27 at the ends thereof and abut directly against surfaces in the body of the boring bar 5. The power transmission functions well thanks to the fact that the piezoceramic elements 25, 27 in this embodiment are embedded in such manner that all their boundary surfaces abut directly against the material of the body of the boring bar 5. The control unit 33 serves to generate such control voltages that the torsional vibrations introduced by the piezoceramic elements 25, 27 are in opposition to the torsional vibrations generated in the turning operation, so that the resulting torsional vibrations of the boring bar 5 are reduced.

The embodiment illustrated in Fig. 2 functions in a manner corresponding to that of the embodiment illustrated in Fig. 3. The difference between the embodiments is the arrangement of the sensors and actuators. In the embodiment in Fig. 2, in the first place vibrations in the lateral direction of the boring bar 5 up and down are counteracted. The control is carried out by the control unit 33 which is connected to all the sensors 17, 19, 21, 23 and the actuators 9, 11, 13, 15. In this embodiment, turning moments are imparted to the boring bar 5, which counteract the bending forces that are generated by the radially and axially directed excitation forces. In this as well as in the other embodiment, the piezoceramic elements 25, 27 are spaced from the centre axis I-I of the boring bar 5. The expression "spaced from the centre axis" relates generally to the fact that the centre axes

of the piezoceramic elements 25, 27 do not coincide with the centre axis of the boring bar 5. If the centre axes should coincide, no turning moment would be obtained, but merely a pure longitudinal change of the boring bar 5.

The control unit 33 is selectable among many different types, such as analog, fed-back control unit, conventional PID regulator, adaptive regulator or some other control unit suitable in a current application. Preferably the control unit strives to control the vibrations towards an optimal state. The control can imply, for example, minimising of the vibrations in one or all directions, in which case the optimal state can be completely extinguished vibrations. A large number of known control algorithms are available. It is desirable to find the most efficient one for the application.

A preferred embodiment of the control system which the control unit 33, the sensors 29, 31 and the piezoceramic elements 25, 27 constitute, is fed back and based on a so-called "Filtered-X LMS-algorithm". It is true that this algorithm is per se known to those skilled in the art. Fig. 4 illustrates an equivalent block diagram of the fed-back control system in a digital description.

Block 401, which is also designated C, represents the dynamic system controlled, which contains the actuators 25, 27 and the sensors 29, 31. The other blocks represent an implementation of said algorithm. Block 405 represents an FIR filter with adjustable coefficients, block 407 represents an adaptive coefficient adjusting means, and block 409 represents a model (C*) of the dynamic system 401.

Seen from a functional, mathematic perspective, the dynamic system constitutes a front filter, whose output signal, i.e. the response of the dynamic system, is $y_c(n)$. The coefficient adjusting means 407 strives to optimise the coefficients of the FIR filter so that an error signal e(n) is minimised. The error signal $e(n)=d(n)- y_c(n)$ where d(n) is a desirable output signal.

The determination of the error signal is carried out by means of a summer 411. To ensure that the coefficient adjusting means converges each time independently of its initial state, it is supplied with a reference signal r(n) from the model 409 of the front filter.

An equivalent description of the control system can be made for the embodiment in Fig. 2.

In mathematical terms it is possible to describe the effect of the invention by saying that it changes the transmission of the tool holder and, more specifically, changes the properties of one or more forward channels, each forward channel being associated with an excitation direction. This way of looking at the matter is equivalent to the effect of the invention being that control vibrations are generated, which influence the vibrations of the tool holder. It should thus be pointed out that in many cases the forward channel cannot be considered time-invariant, i.e. a traditional linear systems theory is in many cases not applicable. The system is usually non-linear.

Alternative Embodiments

The above specification constitutes but a non-limiting example of how the inventive device can be designed. Many modifications are feasible within the scope of the invention as defined in the appended claims. Below follow some examples of such modifications.

The above-described arrangements of the sensors and actuators are examples of arrangements and many variations are possible, such as a combination of those shown or other numbers of actuators, such as two pairs of actuators in each direction or a plurality of actuators adjacent to those shown. In its simplest embodiment, the inventive device comprises only one actuator which comprises one active element. This, however, results in a more non-linear control system, which causes unnecessary technical difficulties in controlling. Therefore it is an advantage to balance the system by arranging, like in the

embodiments shown, the active elements in pairs opposite each other, i.e. opposite each other on each side of the centre axis of the tool holder, such as the elements 9 and 11 in Fig. 2 or the elements 25 and 27 in Fig. 3. A still greater linearity is achieved if each actuator is besides formed of two active elements which are joined, for instance by gluing, with each other, large face to large face, into a double element. The double element will certainly be twice as thick as a single element, but gives a more dynamic effect, which sometimes is preferable.

Besides, the sensors can be of different types. In addition to those mentioned above, e.g. accelerometers and strain gauges are conceivable. The latter, however, are less suitable than the piezoelectric sensors from the environmental point of view.

For immediate and accurate detection of the vibrations, however, the above-described, embedded piezoelectric elements are preferable.

Also the active elements can be of different types within the scope of the invention. In the future, even thinner elements than those used today will probably be conceivable, for instance in the form of piezofilm (PZT). The currently preferred type, however, is piezoceramic elements.

The active elements are in respect of form not bound to be rectangularly parallelepipedal and plate-shaped as the elements shown, but the form may vary according to the application. The plate shape, however, is advantageous since it contributes to minimising the volume of the element. Moreover, an elongate form is a good property which also contributes to imparting to the element a small volume. It is preferred for the dimensional changes to occur in the longitudinal direction of the element.

The arrangement of the active elements in the tool holder may vary and certainly also affects the form. In addition to the above-described, preferred mounting

where the elements certainly are glued to the base of the recess but two opposite power-transmitting surfaces essentially generate the turning moments, other alternatives are possible. One alternative implies that the dimensional change is fully transferred via the glue joint, which in principle is possible with today's strongest glues. Also other variants are contained within the scope of the invention.

The active element is covered by casting, using a suitable material. As an example, plastic materials can be mentioned. Preferably, however, a cover of metal is arranged on top and on the same level as the remaining tool holder surface.

The design of the tool holder varies and may be, for example, T-shaped, the tool being arranged in one end of the crossbar of the T.

## CLAIMS

1. A device for vibration control in a machine for drilling turning, said machine comprising a cutting tool (3) supported by a tool holder (5), the device comprising a control unit (33), a vibration sensor (29, 31) connectible to the control unit, and an actuator (25, 27) connectible to the control unit, and the actuator comprising an active element (25, 27) which converts an A.C. voltage supplied by the control unit to the actuator into dimensional changes, characterised in that said active element is adapted to be embedded in the body of the tool holder, and that said active element is adapted to be embedded in such manner that said dimensional changes impart turning moments to the body of the tool holder.

2. A device as claimed in claim 1, characterised in that said active element (25, 27) is adapted to be embedded with its centre axis spaced from the centre axis of the tool holder (5).

3. A device as claimed in claim 1 or 2, characterised in that said active element (25, 27) is adapted to be embedded close to the surface of the tool holder (5).

4. A device as claimed in any one of the preceding claims, characterised in that said active element (25, 27) is plate-shaped.

5. A device as claimed in any one of the preceding claims, characterised in that said actuator (25, 27) comprises a double element which consists of two active elements which are connected with each other via a large face each.

6. A device as claimed in any one of the preceding claims, characterised in that said active element (26, 27, 45, 47) is a piezoceramic element.

7. A method for vibration control in drilling turning, comprising the steps of detecting the vibrations of a tool holder during working, and generating control vibrations in the tool holder, according to the detected vibrations and by means of at least one active element which is electrically controllable to dimensional changes, characterised by the steps of embedding said active element in the body of the tool holder and, for generating the control vibrations, imparting turning moments to the body of the tool holder by generating at least one control voltage and applying the control voltage across said active element.

8. A method as claimed in claim 7, characterised by carrying out the detection of vibrations piezoelectrically.

9. A method as claimed in claim 7 or 8, characterised by using a Filtered-X LMS-Algorithm as control algorithm for generating the control voltage.

10. A tool holder for drilling turning, the tool holder (5) comprising an actuator (25, 27), said actuator comprising an active element (25, 27) which is electrically controllable to dimensional changes, characterised in that the active element (25, 27) is embedded in the body of the tool holder and is adapted to impart, through said dimensional changes, turning moments to the body of the tool holder.

11. A tool holder as claimed in claim 10, characterised in that said active element (25, 27) is embedded with its centre axis spaced from the centre axis of the tool holder (5).

12. A tool holder as claimed in claim 10 or 11, characterised in that said active element (25, 27) is embedded close to the surface of the tool holder (5).

13. A tool holder as claimed in claim 10, 11 or 12, characterised in that at least one pair of elements is arranged in such manner that the active ele-

ments included in the pair are oppositely arranged on each side of the centre axis of the tool holder (3, 23, 41).

14. A tool holder as claimed in any one of claims 10-13, characterised in that at least one active element (25, 27) is arranged helically round the centre axis of the tool holder (5).

15. A tool holder as claimed in any one of claims 10-14, characterised in that it comprises an embedded, piezoelectric sensor element (29, 31).

16. A tool holder as claimed in any one of claims 10-15, characterised in that said embedded elements (25, 27, 29, 31) are cast into the body of the tool holder (5).

17. A tool holder as claimed in any one of claims 10-16, characterised in that at least one actuator (25, 27) comprises two active elements which are connected with each other via a large face each to form a double element.

18. A tool holder as claimed in any one of claims 10-17, characterised in that said active elements (25, 27) is a piezoceramic element.

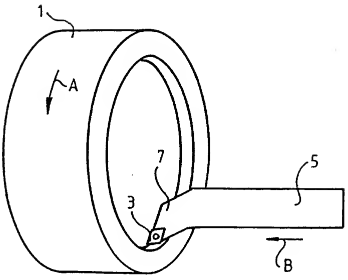


Fig. 1

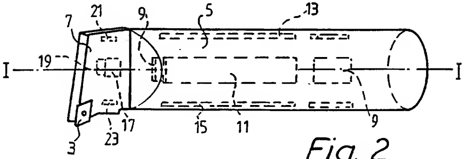


Fig. 2

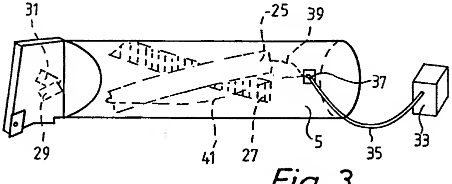


Fig. 3

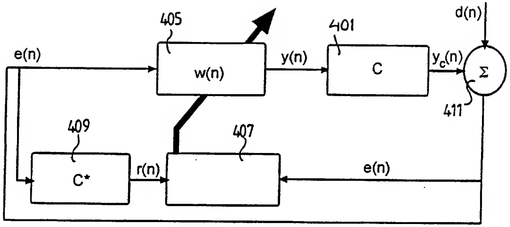


Fig. 4

# INTERNATIONAL SEARCH REPORT

International application No.
PCT/SE 99/01885

**A. CLASSIFICATION OF SUBJECT MATTER**

IPC7: B23B 29/12, F16F 15/00

According to International Patent Classification (IPC) or to both national classification and IPC

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**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| Y | Patent Abstracts of Japan, Vol 12,No 448, M-768 abstract of JP 63-180401 A (MITSUI ENG & SHIPBUILD CO LTD), 25 July 1988 (25.07.88) -- | 1-18 |
| Y | US 5485053 A (BAZ), 16 January 1996 (16.01.96), column 5, line 52 - line 60, figure 32, abstract -- | 1-18 |
| A | US 4849668 A (CRAWLEY ET AL), 18 July 1989 (18.07.89), figure 4, abstract -- | 1-18 |

[X] Further documents are listed in the continuation of Box C. [X] See patent family annex.

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|---|---|---|
| A | WO 9220482 A1 (UNIVERSITY OF KENTUCKY RESEARCH FOUNDATION), 26 November 1992 (26.11.92), figures 2,7, abstract<br>-- | 1-18 |
| A | EP 0715092 A2 (AT&T CORP), 5 June 1996 (05.06.96), figures 1-2, abstract<br>--<br>-------- | 1-18 |

# INTERNATIONAL SEARCH REPORT

Information on patent family members

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| Patent document cited in search report | Publication date | Patent family member(s) | Publication date |
|---|---|---|---|
| US 5485053 A | 16/01/96 | NONE | |
| US 4849668 A | 18/07/89 | NONE | |
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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 7 : B32B 29/12, F16F 15/00

A1

(11) International Publication Number: WO 00/47408

(43) International Publication Date: 17 August 2000 (17.08.00)

(21) International Application Number: PCT/SE00/00242

(22) International Filing Date: 8 February 2000 (08.02.00)

(30) Priority Data:
9900441-8 10 February 1999 (10.02.99) SE

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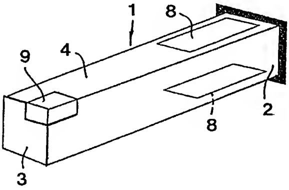
(81) Designated States: JP, US, European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).

**Published**

*With international search report.*
*Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.*
*In English translation (filed in Swedish).*

(54) Title: ACTIVE ANTI-VIBRATION SYSTEM FOR CUTTING TOOLS




(57) Abstract

A tool for chip removing machining comprises a shank (1) having a clamping end (2) together with a machining element (9) at an opposite end. In the area near the clamping end (2), there are piezo-elements (8) having the purpose of dampening bending and/or torsional vibrations. The action of the piezo-elements on the shank may be controlled passively by means of a control module (14) including resistive components (or actively by means of a logical control circuit).

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# ACTIVE ANTI-VIBRATION SYSTEM FOR CUTTING TOOLS

## Technical field of the invention

This invention relates to a tool intended for chip removing machining of the type that comprises a shank having a clamping end and having a machining element at an opposite end.

## Background to the invention

During chip removing machining, such as turning or drilling, problems often arise with vibration, specially in cases where the length of the shank or the tool is at least 4-5 times larger than the diameter thereof. One type of vibration is bending vibration, the shank being bent to and fro and submitted to bending deformations. This phenomenon constitutes a common problem, for instance during turning, specially internal turning, where the shank in the form of a boring bar has to be long in order to reach the workpiece, at the same time as the diameter of the bar is limited by the dimension of the hole in which machining is carried out. During such drilling, turning and milling operations, where the distance to the workpiece is large, extension units are used, which frequently cause bending vibration leading not only to deteriorated dimensional accuracy and irregularities in the workpiece, but also to reduced service life of the milling cutter and its cutting insert or the machining element thereof.

Another type of vibration is torsional vibration, the shank being turned or screwed to and fro around the longitudinal axis thereof during which shear strain is created. Such vibration arises, for instance, during drilling, specially at higher speed. Also torsional vibration leads to a poorer quality of the machined surface, as well as reduced service life of tools and cutting inserts. An important nuisance is also the working environment problem which torsional vibrations give rise to, in that a shrill noise is generated during rotation.

Prior art

Dampening of vibrations in tools for chip removing machining has previously taken place by pure mechanical dampening, the shank being formed with a cavity in which a mass of, for instance, counter-vibrating heavy metal is applied. In doing so, the weight and the position of the mass is tuned in order to bring about dampening of the vibration within a certain range of frequencies. The cavity is then filled with a viscous liquid, e.g. oil, and is plugged. However, this technique works tolerably well only in those cases where the length of the shank is approx. 4-10 times longer than the diameter thereof. In addition to this limitation, the pure mechanical dampening has an obvious disadvantage inasmuch as the range of frequencies within which the dampening acts is very limited. An additional nuisance consists of the weakening of the structural strength, which the cavity formed in the shank entails.

In entirely different technology areas, a development of more efficient, adaptive dampening techniques, has been started with the utilization of, among other things, piezo-elements. A piezo-element consists of a material, most often of a ceramic type, which on compression or strain in a certain direction - the direction of polarization - generates an electric field in this direction. The piezo-element is usually in the shape of a rectangular plate with a direction of polarization, which is parallel to the major axis of the plate. By connecting the piezo-element to an electrical circuit, including a control module, and compressing or elongating the piezo-element in the direction of polarization, an electric current will be generated and flow in the circuit, electric resistive components included in the control module releasing heat according to known physics. In doing so, vibration energy is converted to thermal energy, whereby a passive dampening, but not totally neutralizing effect on the vibration is obtained. What is more, by forming the control module with a suitable combination of resistive and reactive components, so called shunts, selected frequencies may be brought to be dampened particularly effectively. Such frequencies are advantageously the so called "eigenvalue" frequencies of the exposed eigenmodes of the object in question, which are the ones that are especially excited.

Conversely, a piezo-element may be compressed or elongated by the fact that an electric voltage is applied over the piezo-element, and this may be used as a control device or operating device (actuator). This may, then be used for an active vibration reduction by the fact that the polarity of the applied electric voltage is chosen in such a way that the mechanical stress of the operating device acts in the opposite direction, as an external, mechanical stress, the emergence of vibration being suppressed by the fact that other kinetic energy, for instance energy of rotation, is not permitted to translate into vibration energy. The synchronization of the applied electric voltage in respect to the external mechanical tension, the effect of which should be counteracted, is then carried out by the fact that a feedback signal from a deformation sensitive sensor is fed to a control means in the form of a logical control circuit, e.g. a programmable microprocessor, in which the signal is processed to almost instantaneously control the electric voltage applied over the operating device. The control function, i.e. the relation between the input signal from the sensor and the output voltage, may then be made very complex. A self-learning system for adaptation to varying conditions is, for instance, feasible. The sensor may consist of a separate, deformation sensitive device, e.g. a second piezo-element, or be common with the operating device.

Examples of realized applications and current development areas for utilization of piezo-elements in vibration dampening purposes are described in Mechanical Engineering, Nov 1995, p. 76-81. Thus, skis for alpine skiing (K2 Four ski, K2 Corp., USA) have been equipped with piezo-element with the purpose of repressing undesired vibration, which otherwise decreases the contact with the ground and thereby reduces the skier's prospect of a stable and controlled skiing. Furthermore, applications such as increased wing stability of aeroplanes, improved comfort in motor vehicles, suppression of vibrations in rotor blades and shafts of helicopters, vibration reduction of machining platforms for flexible manufacture, and increased hit precision of military weapons are mentioned. In data sheets from Active Control eXperts (ACX) Inc., USA (manufacturer of piezo-elements) vibration reduction of snowboards is also mentioned.

Objects and features of the invention

The present invention aims at managing the shortcomings of previously known tools for chip removing machining mentioned in the introduction and at providing a tool with an improved vibration dampening. Thus, a primary object of the invention is to provide a robust tool with the ability to efficiently dampening of vibrations over a wide range of frequencies, for instance where the length of the shank is 3-15 times larger than the diameter thereof, preferably approx. 4-6 times longer than the diameter thereof. It is also an object to provide a tool for chip removing machining having a longer service life for the tool itself as well as the cutting element thereof, compared to previously known tools. Additional objects of the tool are that the use thereof should lead to an increased quality of the surface of the machined workpiece and to an improved working environment by reduction of high frequency noise.

According to the invention, at least the primary object is attained by the features defined in the characterizing part of claim 1. Preferred embodiments of the invention are furthermore defined in the dependent claims.

Brief Description of the Appended Drawings

In the drawings:

| | |
|---|---|
| Fig 1 | is a schematic side view of a long narrow body in the form of a tool shank during bending deformation during turning (1st resonance requency), |
| Fig 2 | is a graph showing the bending moment in the body, |
| Fig 3 | is a side view of a cross sectional end portion of the body adjacent to a clamping end so as to illustrate the tension proportional to strain in the body during bending deformation, |
| Fig 4 | is a schematic side view of a long narrow body during torsional or shear strain, |
| Fig 5 | is a graph showing the torsional moment during the last-mentioned deformation, |

Fig 6 is a circular cross-section through the body according to fig 4 so as to illustrate the shear strain proportional to shear strains in the body,

Fig 7 is a view of a portion of a body showing deformation of a surface portion during torsional stress,

Fig 8 is a transparent perspective view of a tool shank according to the invention,

Fig 9 is a perspective view of a bar extender for milling tools formed with circular cross-section,

Fig 10 is a side view of a drilling tool according to the invention,

Figs 11-13 are perspective views of tool shanks with quadratic cross-sections and in different alternative embodiments,

Fig 14 is a perspective view of a tool for active vibration dampening mounted in a carrier, and

Fig 15 is an analogous perspective view of an alternative embodiment for passive vibration dampening.

Brief description of general deformation cases

In figs 1-7, different deformation cases during which oscillations or vibrations may arise are shown schematically.

In fig 1, a long narrow body is illustrated which may consist of a tool or a shank of a tool. The body 1 has a clamping end 2 and a free, outer end 3. The body has an external surface 4, which may consist of an envelope surface if the body is cylindrical. It may also include a plurality of plane surfaces if the body has a polygonal, e.g. square cross-sectional shape. The body 1 may have an arbitrary cross-sectional shape, however, most are usually circular or square. In fig 1, numeral 5 designates a part in which the body 1 is clamped, the body extending console-like from the clamping part. In fig 1, the body 1 is shown in a state when it has been deformed in a first bending eigenmode. Furthermore, a graph is shown in fig 2, which illustrates how the bending moment $M_b$ in this case varies along the body. As is seen in the graph, a largest bending moment, and thus a largest strain, arises at or near the clamping end 2. The same is valid for all lower modes, which are normally dominating energy-wise during bending vibration of tools

for chip removing machining. In fig 3, a portion of the body 1 deformed by deflection in fig 1 is shown in the area of the clamping end. In doing so, how the strain at bending deformation varies in the cross-direction of the body (the strain is highly exaggerated for illustrative reasons) is illustrated. As is seen in the figure, the largest strains are obtained at the envelope or outer surface 4 of the body.

In fig 4, a long narrow body 1 is shown which has been deformed in a first torsional eigenmode. Furthermore, in fig 5 a graph is shown which illustrates how the torsional moment $M_t$ in this case varies along the body. As is seen in the graph, the largest torsional moment, and thus the largest shear strain, is obtained closest the clamping part 5. The same is valid for all lower modes, which are normally dominating energy-wise during torsional vibration of tools for chip removing machining. In fig 6, a circular cross-section of the body 1 according to fig 4 is shown, illustrating how the shear strain at shear deformation varies along the diameter of the cross-section (the shear strain is highly exaggerated for illustrative reason). As is seen in the figure, the largest shear strain is obtained closest the envelope surface 4.

In fig 7, a portion of the body 1 is shown, illustrating deformation during torsional stress of two hypothetical, square surfaces 6, 7 applied on the envelope surface 4, which surfaces are oriented with the edges thereof along and perpendicularly, as well as in 45° degree's angle to the longitudinal extension of the body 1 (the deformation is highly exaggerated for illustrative reason). As is seen in the figure, the surface 6 will, at shear strain, be deformed to a rhombic shape, while the surface 7 is deformed to a rectangular shape. During bending deformation, essentially the opposite relationship will be obtained, in the case where the bending is carried out across the plane of the surfaces 6, 7, i.e. the surface 6 will be deformed to a rectangular shape, while the surface 7 is deformed to a rhombic shape.

Detailed description of preferred embodiments of the invention

In fig 8, a fundamental design of a long narrow tool or shank 1 is shown schematically in which two flat-shaped, rectangular piezo-elements 8 are fastened on opposite, longitudinal plane surfaces 4 of the shank formed with square cross-section. The piezo-

elements 8 are placed in the area near the clamping end 2 of the shank. At the outer end 3 thereof, the shank has a machining element in the form of a cutting insert 9. Thus, the piezo-elements 8 are positioned in an area where the largest strain occurs at bending deformation as well as torsional deformation. Although this location is preferred, other locations are also feasible. Furthermore, the piezo-elements 8 are oriented with the major faces thereof essentially parallel to the plane surfaces 4 of the shank and with the major axes essentially parallel to the length extension of the shank 2, and the piezo-elements 8 during bending vibration will be deformed whilst retaining a rectangular shape, while the same at torsional vibration will be deformed to a rhombic shape (compare fig 7). The direction of polarization of the flat-shaped, rectangular piezo-elements is here, and in the following, assumed to be parallel to the major axes of the same, although another shape as well as another direction of polarization is feasible. Thereby, the piezo-elements act, at the orientation in question of the same, most efficiently for dampening of bending vibration, since the same in this case undergo a maximum average deformation along the direction of polarization.

The relationship between the size of the piezo-elements 8 and the size of the shank in fig 8 and the following figures should not be understood as limiting, but are only selected in order to make the exemplified location and orientation of the piezo-elements clear. The number of piezo-elements and their orientation shown in the figures should not be regarded as limiting but only as exemplifying. Neither need a plurality of piezo-elements formed on the shank have the similar location, size, shape or orientation. The number of piezo-elements may vary, but should, however, for reasons of balance, amount to at least two.

In fig 9, an embodiment is shown according to which the body 1 consists of a bar extension with a circular cross-section intended for milling tools. In this case, a cutting machining element 9 in the form of an edge formed adjacent to a chip pocket 10 at the free end 3 of the bar extension. A piezo-element 8 is attached to the envelope surface 4 of the bar extension in an area near the clamping end 2. The major axis of the piezo-element is parallel to the length extension of the bar extender. Consequently, with this

orientation the piezo-element 9 acts most efficiently for dampening of bending vibration also here.

Fig 10 shows another embodiment example where the body or the tool 1 consists of a drill with a shank having a circular cross-section and a so called adapter. A piezo-element 8 is attached on the tool with the major axis thereof at an approx. 45° angle to the length extension of the tool. Thereby, the piezo-element acts most efficiently for dampening of torsional vibrations (compare fig 7).

For a simultaneous dampening of bending and torsional vibrations, the shank of the tool is advantageously formed with a plurality of piezo-elements of which some are oriented with the long sides thereof essentially parallel to the length extension of the shank, while other are oriented at approx. 45° angle. Alternatively, one or more piezo-elements have other orientations between these orientations in order to individually achieve sensitivity for both bending and torsional vibrations.

Piezo-elements are usually fragile, especially those of a ceramic type. Therefore, in demanding environments they should have some form of protection to achieve an acceptable service life. In figs 11-13, a tool shank with a quadratic cross-section is shown, the piezo-elements 8 being attached and protected in alternative ways. In all cases, the piezo-elements are placed in an area near the clamping part 5 (this one may consist of a conventional clamping in which the tool is detachably mounted). In fig 11, the piezo-element 8 is mounted in a recess 11 and advantageously covered by a protective coat, for instance of epoxy type. In fig 12, the piezo-element is assumed to be mounted in the countersink 11 and covered by a stiff lid 12. In fig 13, the piezo-element 8 is mounted, e.g. fixed by cement, on the outside of the shank. These alternatives should only be seen as examples of which the ones shown in fig 11 and 12 are preferred. It will be appreciated that the same type of protection for the piezo-elements is independent of the cross-section shape of the tool shank.

According to the invention, the piezo-elements may co-operate with means for electric control or steering of the same. In figs 14 and 15, examples are shown of how the tool 1

has been formed with such control means. In these cases, the tool is mounted in a carrier 13. In fig 15, a control means for passive dampening is shown in the form of a control module 14 formed near the clamping end 2 and an electric connection 15, via which two piezo-elements 8 are connected to the control module 14 for a separate or common control of the respective piezo-element. This module 14 comprises at least electric resistive components. Preferably the control module 14 also comprises one or more shunts, and selected frequencies may be dampened specially effectively.

Fig 14 illustrates a control means for active dampening in the form of a detached logical control circuit 16, e.g. a programmable microprocessor, for separate or common control of (via the schematically shown electric connection 15) the voltage applied over the piezo-element 8. In practice, the connection 15 may in this case comprise collector shoes or the like. Even if the piezo-elements 8 in the embodiment exemplified in fig 14 for active dampening at the same time act as both operating devices and sensors, it is feasible to achieve these two functions by separate operating device and sensors, the sensors do not need to consist of piezo-elements. Although the exemplified location of the control module 14 and the logical control circuit 16, respectively, is preferred, also other locations are feasible. For instance, it is feasible to, like the logical control circuit 16, form the control module 14 detached from the tool. The advantage of placing the control module 14 near the clamping end is that the module is easy to connect to the piezo-elements, while the same at a separate placing becomes easier to protect against harmful mechanical actuation.

A robust tool for chip removing machining with the ability to not only passive but also active dampening of bending as well as torsional vibrations over a wide range of frequencies is provided by the invention. Furthermore, a tool is provided which, on the one hand, presents a longer service life for the tool itself as well as the cutting or machining elements thereof and, on the other hand, brings about an increased quality of the surface on the machined workpiece. In addition, an improved working environment is attained through the reduction of high frequency noise in comparison with previously known tools.

Feasible modifications of the invention

The invention is not solely restricted to the embodiments and applications described and shown in the drawings. Thus, it is feasible to, by active control of the piezo-elements, introduce or reinforce vibrations if these are desirable, e.g. during chip breaking. Relatively large amplitudes may be obtained for introduced or reinforced vibrations with frequencncies near the eigenvalue frequencies of the tool.

Claims

1. Tool for chip removing machining including a shank (1) having a clamping end (2) and having a machining element (9) at an opposite end, c h a r a c t e r i z e d in, that the same comprises one or more piezo-elements (8) having the purpose of dampening vibrations therein.

2. Tool according to claim 1, c h a r a c t e r i z e d in, that the piezo-element (8) is placed in an area near the clamping end (2).

3. Tool according to claim 1 or 2, c h a r a c t e r i z e d in, that the piezo-element (8) is applied in a recess (11) formed in the tool.

4. Tool according to any one of the preceding claims, c h a r a c t e r i z e d in, that the piezo-element (8) is attached on an external surface of the tool.

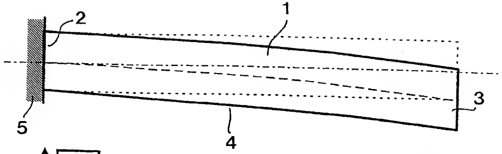
5. Tool according to any one of the preceding claims, c h a r a c t e r i z e d in, that the piezo-element (8) co-operates with a control module (14) having the purpose of receiving electric voltage generated by the piezo-element and transform this electric energy to thermal energy.

6. Tool according to any one of claims 1 - 4, c h a r-a c t e r i z e d in, that the piezo-element (8) is actively controllable through the application of electric voltage from an outer voltage source via a control means in the form of a logical control circuit (16).

7. Tool according to any one of the preceding claims, the piezo-element (8) being flat-shaped and having a major face in which an appurtenant direction of polarization is lying, c h a r a c t e r i z e d in, that the major face is essentially parallel to an external surface (4) of the tool.

8. Tool according to claim 7, c h a r a c t e r i z e d in, that the direction of polarization of the piezo-element (8) is essentially parallel to the longitudinal extension of the tool shank (1) so that the piezo-element primarily dampens bending vibrations.

9. Tool according to claim 7, c h a r a c t e r i z e d in, that the direction of polarization of the piezo-element (8) extends in substantially an 45° angle to the longitudinal extension of the tool shank so that the piezo-element primarily dampens torsional vibrations.



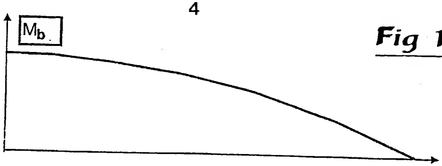




Fig 1

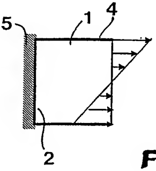



Fig 2

Fig 3

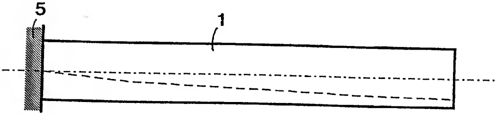



Fig 4

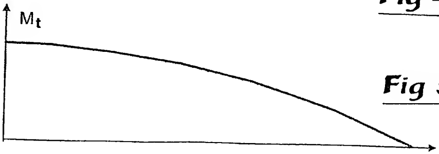



Fig 5

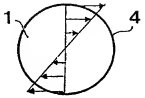



Fig 6

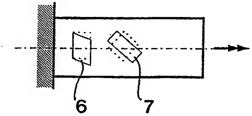



Fig 7

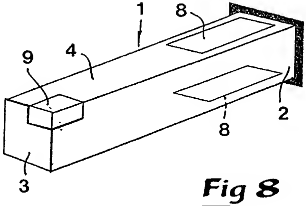



Fig 8

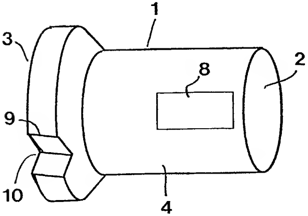



Fig 9

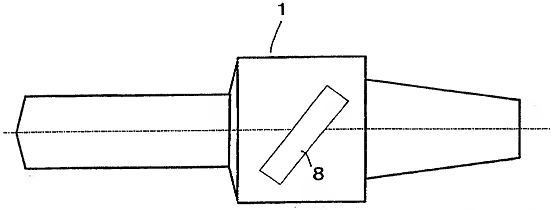
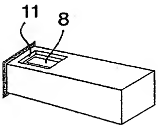
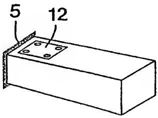



Fig 10



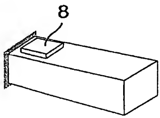
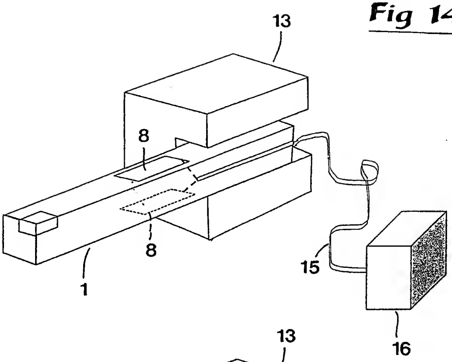




Fig 11

Fig 12

Fig 13

Fig 14



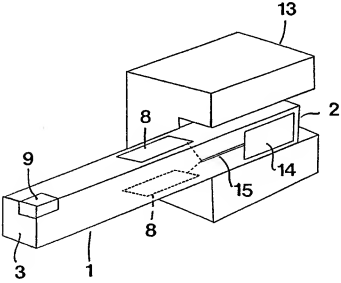




Fig 15

# INTERNATIONAL SEARCH REPORT

International application No.
PCT/SE 00/00242

A. CLASSIFICATION OF SUBJECT MATTER

IPC7: B32B 29/12, F16F 15/00
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC7: B23B, B23Q

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

SE,DK,FI,NO classes as above

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

WPI, EPODOC, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
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[X] Further documents are listed in the continuation of Box C. [X] See patent family annex.

* Special categories of cited documents:
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"&" document member of the same patent family

| Date of the actual completion of the international search | Date of mailing of the international search report |
|---|---|
| 29 May 2000 | 06-06-2000 |
| Name and mailing address of the ISA<br>Swedish Patent Office<br>Box 5055, S-102 42 STOCKHOLM<br>Facsimile No. +46 8 666 02 86 | Authorized officer<br><br>Joakim Movander/OGU<br>Telephone No. +46 8 782 25 00 |

## INTERNATIONAL SEARCH REPORT

International application No.
PCT/SE 00/00242

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02/12/99

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| SE 9803606 A | 22/10/98 | NONE | |
| SE 9803605 A | 22/10/98 | NONE | |

## INTERNATIONAL SEARCH REPORT

International application No.
PCT/NO 2004/000330

**A. CLASSIFICATION OF SUBJECT MATTER**

IPC7: B23B 29/02 // B23B 29/00

According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)

IPC7: B23B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

SE,DK,FI,NO classes as above

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-INTERNAL, WPI DATA, PAJ

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
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"&" document member of the same patent family

| Date of the actual completion of the international search | Date of mailing of the international search report |
|---|---|
| 8 March 2005 | 08-03-2005 |
| Name and mailing address of the ISA/<br>Swedish Patent Office<br>Box 5055, S-102 42 STOCKHOLM<br>Facsimile No. +46 8 666 02 86 | Authorized officer<br><br>Fredrik Strand / MRo<br>Telephone No. +46 8 782 25 00 |

# INTERNATIONAL SEARCH REPORT

International application No.
PCT/NO 2004/000330

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